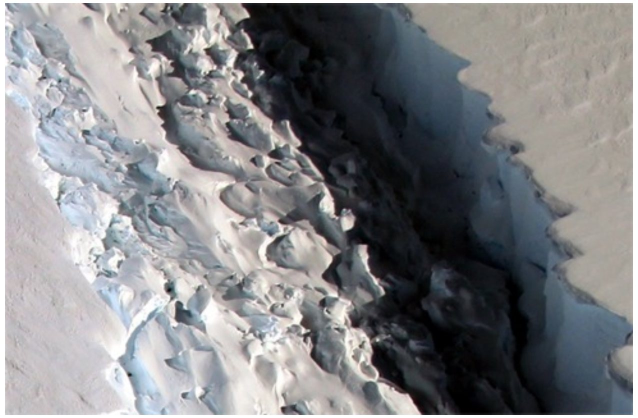
SCIENCE






Surface Biology and Geology Designated Observable

- ➢ Architecture Studies

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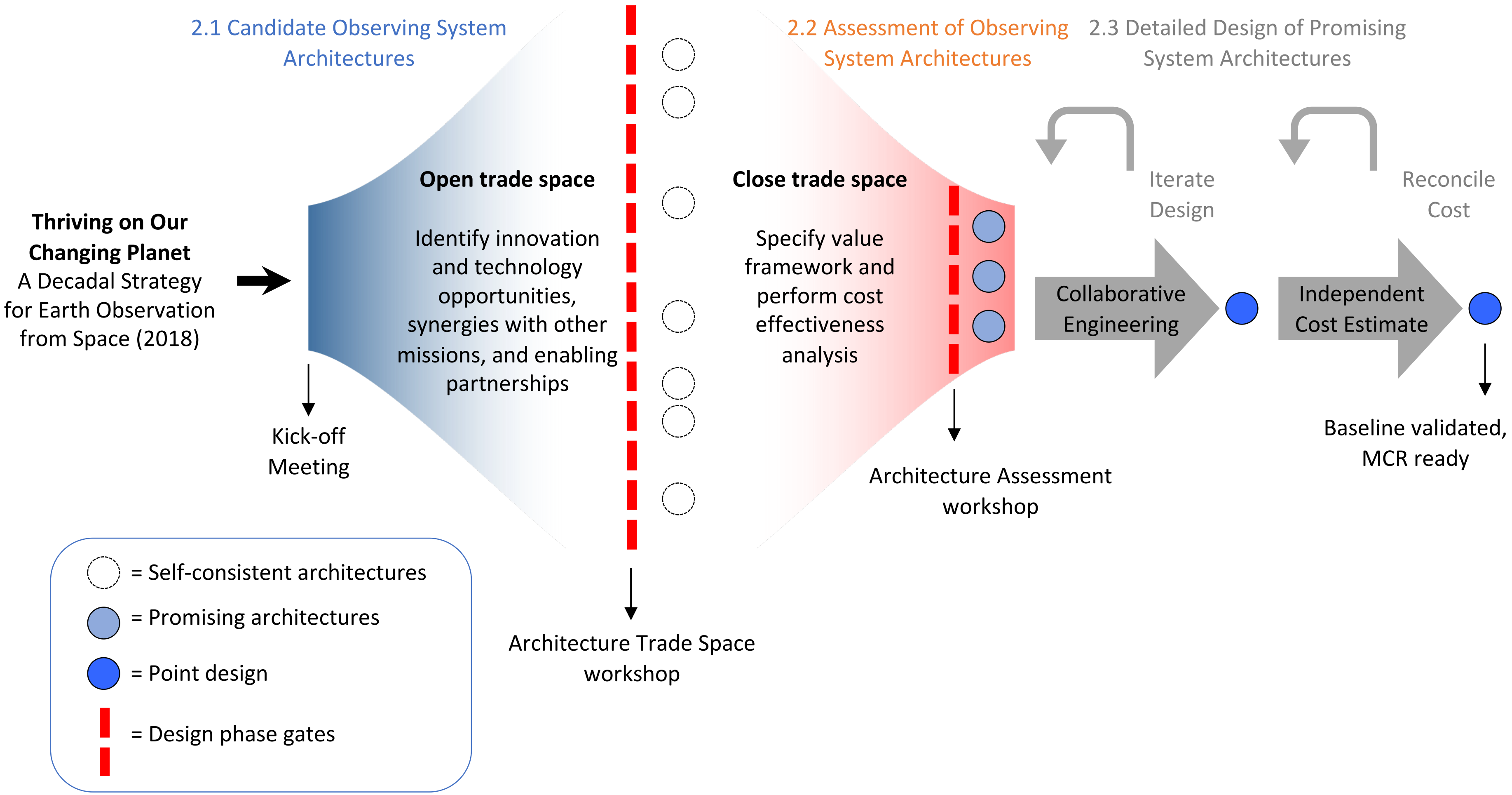
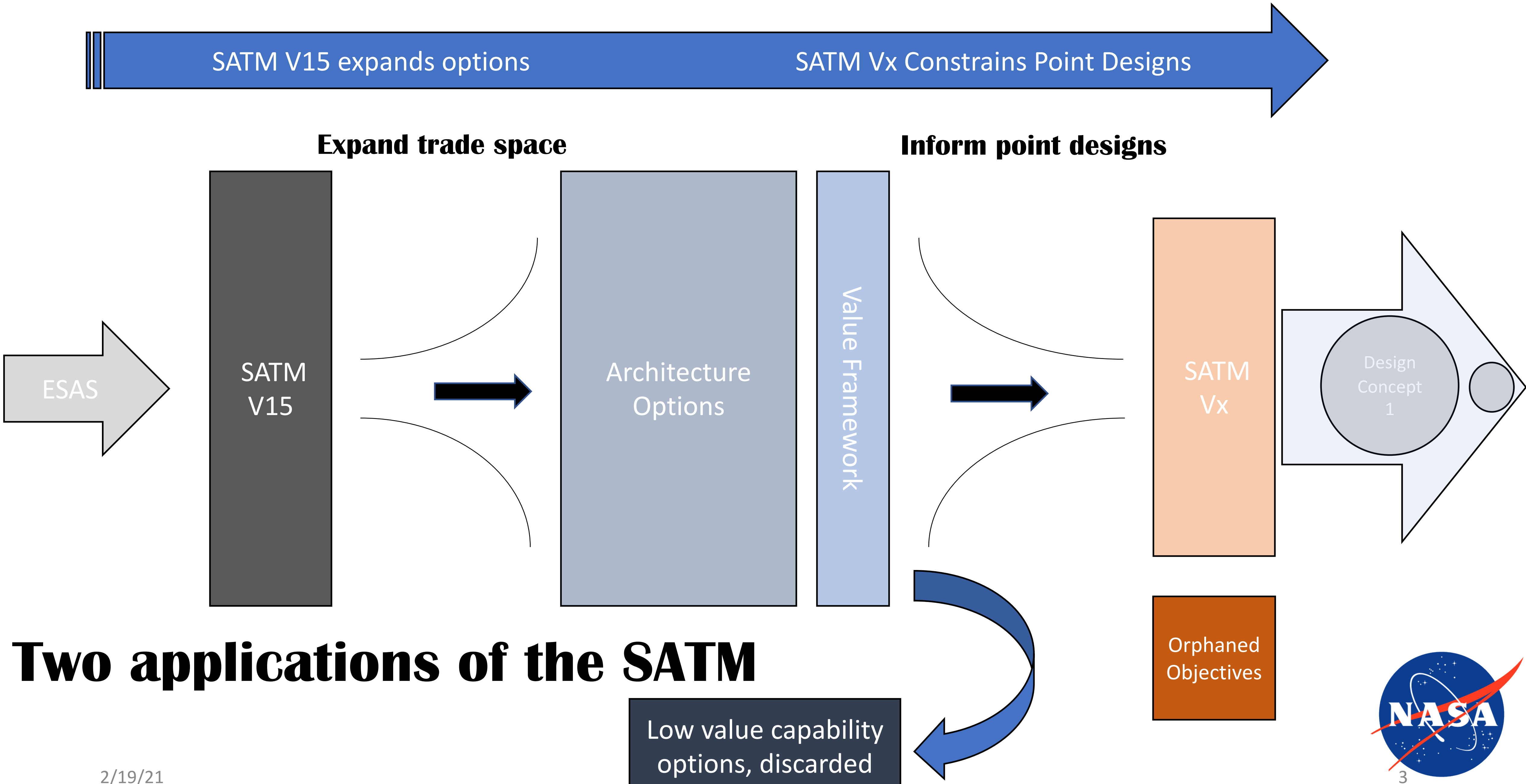
SBG Architecture Study Team

July 9, 2019

Evolution of a Concept



Two applications of the SATM



Draft SATM (Part I) - Illustrative

STM for DS Targeted Observables TO-18 (Surface Biology & Geology)														
Decadal Survey Science Topics, Questions, Objectives, and Geophysical Observables					SBG Example Geophysical Variables and Capabilities									
Topic	DS Science Question	DS Science/Application Objective	Priority	DS Suggested Geophysical Parameters	Example Geophysical Parameters (SBG)	VSWIR Spatial	VSWIR Temporal	VSWIR Range	VSWIR Sensitivity	TIR Spatial	TIR Temporal	TIR Range	TIR Sensitivity	Notes
Global Hydrological Cycles and Water Resources	**H-1.** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	**H-1c.** Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.	Most Important	Snow and glacier albedo and surface temperature. Spectral albedo of suxbpixel snow and glaciers at weekly intervals to an accuracy to estimate absorption of solar radiation to 10%.Ice/snow temperature to ± 1K. At spatial resolution of 30 to 100 m.	Snow coverage fraction over cryosphere	B	C	A	B					1,8
					Snow spectral albedo From Visible to Thermal	B	B	A	B	A	B	B	A	1,8
					Snow surface temperature					A	B	B	A	4,5,8
	H-2. How do anthropogenic changes in climate, land use, water use, and water storage, interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?	**H-2a.** Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling.	Very Important	Latent heat flux. 3 (desirable) to 6 hour (useful) resolution during daytime intervals and at 1 km spatial scale with better than 10 W/m2 accuracy. Requires temperature of soil and vegetation separately at 40-100m spatial resolution, accuracy of +/- 1K, at temporal frequency to resolve the diurnal cycle. Albedo of soil and vegetation separately to an accuracy to estimate absorption of solar radiation to 10 W/m2, at weekly intervals at field scale, 30-60m spatial resolution.	Global VSWIR Spectral surface reflectance	B		A						7,8
					TIR emissivity					A	B		A	4,5,8
					Evapotranspiration rates of vegetation canopies at different times of day with 10% uncertainty					B	B	B	A	4,5,8
					Surface temperature at different times of day					A	B	B	A	4,5,8
	H-4. Hazards, Extremes, and Sea-level Rise. How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?	**H-4a.** Monitor and understand hazard response in rugged terrain and land margins to heavy rainfall, temperature and evaporation extremes, and strong winds at multiple temporal and spatial scales.	Very Important	Magnitude and frequency of severe storms. Depth and extent of floods. Precipitation, snowmelt, water depth, and water flow in soil at time and space scales consistent with events.	(See H1-c)									
	W-3. How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, cryosphere) and thereby influence weather and air quality?	**W-3a.** Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress) to an accuracy of 10 W/m2 in the enthalpy flux, and 0.1 N/m2 in stress, and observe total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.	Very Important	**Land SurfaceTemperature.** 0.6 K random uncertainty in 25 × 25 km area, 80% daily coverage, 3-5 km resolution, with 1 km resolution desired.	Land surface temperature (3-5 day repeat)					B	B	B	A	4,5,8
					Land surface temperature (derived, daily repeat)					C	A			4,5,8
Marine and Terrestrial Ecosystems and Natural Resource Management	**E-1. Ecosystem Structure, Function, and Biodiversity.** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?	**E-1a.** Quantify the global distribution of the functional traits, functional types, and composition of vegetation spatially and over time.	Very Important	**Chemical properties of vegetation, aquatic biomass, and soils. (Land, inland aquatic, costal zone, and shallow coral reef):** Spectral radiance (10nm; 380-2500nm); GSD = 30-45m; Revisit = ~15 days; SNR = 400:1 VNIR/250:1 SWIR @ 25% reflectance; IT of ~5 ms.	Biogeochemical traits of aquatic biomass (coastal)	A	C	C	A					8
					Benthic composition	A	C	C	A					8
					Chemical Properties of Canopies	A	C	A	A					8
					Soil Properties	A	C	A	A					8
					Terrestrial Veg. functional traits, types, composition	A	C	A	A					8
					Terrestrial Veg. species (where possible)	A	C	A	A					8
				Chemical properties of vegetation, aquatic biomass, and soils (Ocean): Spectral radiance (5 nm; 380-1050 nm); GSD 0.25-1.0 km; Revisit =< 2 days; SNR = 1000:1 @ TOA clear sky ocean radiance (PACE)										
		E-1c. Quantify the physiological dynamics of terrestrial and aquatic primary producers.	Most important	**Primary Obsrvable: Chemical properties of vegetation, aquatic biomass, and soils (Land, inland aquatic, costal zone, and shallow coral reef)**: Spectral radiance (10nm; 380-2500nm); GSD = 30-45m; Revisit = ~15 days; SNR = 400:1 VNIR/250:1 SWIR @ 25% reflectance; IT of ~5 ms.	See E-1a.									
				Secondary Observable, Solar-induced fluorescence: 400-790 nm; 0.3 nm bandwidth (FWHM).										
				Primary Obsrvable, Chemical properties of vegetation, aquatic biomass, and soils (Ocean): Spectral radiance (5 nm; 380-1050 nm); GSD 0.25-1.0 km; Revisit =< 2 days; SNR = 1000:1 @ TOA clear sky ocean radiance (PACE)										
	E-2. Fluxes Between Ecosystems, Atmosphere, Oceans, and Solid Earth. What are the fluxes (of carbon, water, nutrients, and energy) between ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing?	**E-2a.** Quantify the fluxes of CO2 and CH4 globally at spatial scales of 100-500 km and monthly temporal resolution with uncertainty < 25% between land ecosystems and atmosphere and between ocean ecosystems and atmosphere.	Most Important	**GPP, respiration, and decomposition, and biomass burning.** Global, daily, 30 m / 300 m	GPP									
					Ecosystem respiration									
					Decomposition									
					Biomass Burning									
	E-3. Fluxes Within Ecosystems. What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?	E-3a. Quantify the flows of energy, carbon, water, nutrients, and so on sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types.	Most important	**GPP, respiration, litterfall and decomposition, nonPS vegetation, functional types.** Global, daily, 30 m / 300 m.	See E-1a.									
					Non-photosynthetic vegetation	A	A	A	A					
				Daily SIF measurements										

Key SATM Performance Objectives

- Derived from the Decadal Survey and shown in the SATM
- Provided in the RFI to identify all candidate observing architectures

Performance Parameters	Spectral Range	Spectral		GSD	Revisit	Coverage	Local Time for Acquisition
VSWIR	0.35 or 0.4 to 2.5µm	Resolution: 10nm or better Coverage: Continuous	SNR: VNIR: >400 SWIR: >250	30-45m	2-16 days	Global	10:30am to 1:30pm
TIR	8 to 12µm 3 to 5µm	Bands: >5 desired	NEdT: <0.2 K	40-60m	1-7 days	Global	Can vary across the diurnal cycle

The primary goal of the architecture study is to determine the extent to which any given architecture meets all, most, or some of the objectives derived from these priorities within the budget and schedule constraints recommended in the Decadal Survey. All observational architecture concepts and measurement capabilities achieving performance parameters within the ranges in this table are considered. An observational system can include any combination of a program of record, space and/or airborne systems.

Preferred Observing Strategy

• Plant traits	Spectral performance
• Evapotranspiration	Temperature versus emissivity, frequency
• Minerals	Spectral performance
• Aquatic biology	Spectral performance, frequency
• Snow	Frequency
• Fire	Frequency, 4 micron dynamic range
• Volcanic gases	Frequency
• Natural Hazards	Frequency

Mow the lawn

+ Pointing

SPACECRAFT CAPABILITY DESCRIPTIONS

FLAGSHIP SATELLITE

S/C Mass Range	DC Power	Payload Mass
2000-2500 kg	1000-1800 W	800-1000 kg
Payload Volume	**Constellation Size**	**Instrument Performance**
~4x2x2 m^3	1	Very Good

A flagship spacecraft in the vein of AURA, AQUA, or TERRA. Has a wide suite of instrument modes for observation. Instrument suite addresses multiple DOs. Compatible with the larger class of launch Vehicle, e.g. Falcon-9, Vulcan. Platform accommodates both VSWIR and TIR instruments with generous margins.

LARGE SATELLITE

S/C Mass Range	DC Power	Payload Mass
1000-2000 kg	500-1500 W	400-600 kg
Payload Volume	**Constellation Size**	**Instrument Performance**
~3x1.5x1.5 m^3	1	Very Good

Spacecraft on the scale of LANDSAT-7 or LANDSAT-8. Platform carries both VSWIR and TIR instruments. Compatible with the larger class of launch Vehicle, e.g. Falcon-9, Vulcan. Platform easily accommodates both VSWIR and TIR instruments .

MEDIUM SATELLITE

S/C Mass Range	DC Power	Payload Mass
500-1000 kg	200-700 W	200-400 kg
Payload Volume	**Constellation Size**	**Instrument Performance**
~1.75x1x1 m^3	1-2	Very Good

Spacecraft on the scale of the LeosSTAR-2 bus flown on OCO-2 or Ball's BCP 2000 spacecraft used for Icesat. Platform may carry both VSWIR and TIR instruments, or use separate platforms.

SMALL SATELLITE

S/C Mass Range	DC Power	Payload Mass
100-300 kg	100-300 W	40-120 kg
Payload Volume	**Constellation Size**	**Instrument Performance**
~0.8x0.5x0.5 m^3	2-4	Good

Spacecraft on the order of Ball's BCP-100 or smaller versions of the NGIS LeoStar-2, or the OneWeb bus from AirBus. Compatible with smaller launch vehicles such as Electron, Pegasus, Virgin Orbit. ESPA-ring compatible up to 180 kg. ESPA-ring Grande compatible at 180-300 kg mass range. Only one instrument per platform. Volume constraints may impose some compromise on instrument performance, e.g. swath coverage or spatial resolution

MICROSAT

S/C Mass Range	DC Power	Payload Mass
30-125 kg	30-125 W	12-25 kg
Payload Volume	**Constellation Size**	**Instrument Performance**
~0.6x0.45x0.45 m^3	Up to 6	Moderate

Larger than a 12U. Typical example is SkyBox from SSL.. ESPA-ring compatible. Smaller dimensions available for payload mean each satellite can only provide fractional capability, e.g. reduced swath, coarser spatial resolution, or reduced spectral range, or number of bands. Compatible with smaller launch vehicles such as Electron, Pegasus, Virgin Orbit.

CUBESAT

S/C Mass Range	DC Power	Payload Mass
5-20 kg	10-120 W	2-4 kg
Payload Volume	**Constellation Size**	**Instrument Performance**
~0.1x0.2x0.3 m^3	10-30	Fair

3U to 12U cubesat platforms, available as product lines from multiple vendors for LEO. Small dimensions available for payload mean each satellite can only provide fractional capability, e.g. reduced swath, coarser spatial resolution, or reduced spectral range, or number of bands. Compatible with standardized P-Pod launch adapters with many options for flight as secondary payloads.

SBG-relevant ESTO Instrument Investments*

Concept	PI	Proposal Number	PI Email Address	Spectral Range	Spectral res (nm)	Instrument Dimensions (cm)	Ang. Res. (mrad)	FOV (deg)	TRL	Comments
Hyperspectral TIR from GEO	D. Tratt (Aero)	ATI-QRS-14-0006	david.m.tratt@aero.org	8 – 13.5 µm	85	23 x 25 x 20	1	6.4 deg	2	10km IFOV
Hyperspectral Land Imager for SLI	T. Kampe (Ball)	SLIT-15-0023	tkampe@ball.com	0.2 - 2.5 µm		50 x 50 x 50		7.5	4	The VNIR channel (372 to 1015 nm) spectral resolution from 0.45 to 7.5 nm. The SWIR channel operates from 940 nm to 2.5 µm with spectral sampling of 5 to 10 nm
SWIS	H. Bender (JPL)	IIP-13-0040	holly.a.bender@jpl.nasa.	.35 - 1.7 µm	5.7	20 x 10 x 10	0.3	10	6	2U instrument
Chrisp Compact VSWIR Spectrometer	R. Lockwood (MIT/LL)	IIP-16-0017	ronald.lockwood@ll.mit.	.4 - 2.4 µm		7 x 8 x 8		7.8	2	Lockwood, Ronald - 0997 - MITLL <ronald.lockwood@ll.mit.edu>
Multi-band uncooled Radiometer (MURI)	P. Ely (DRS)	IIP-16-0042	philip.ely@drs.com	7 - 12 µm; 6 bands	100 - 1000	66x31x33	0.14	2	4	4U instrument for a/c. S/C version is larger: 100x66x71 cm
HySICS	G. Kopp (U CO)	IIP-10-0019	Greg.Kopp@LASP.Colorad	.35 - 2.3 µm	8		0.7	10	5	
Computational Reconfigurable Imaging Spectrometer (CRISP)	A. Milstein (MIT/LL)	ACT-17-0032	milstein@ll.mit.edu	7 - 13 µm	129	60	0.4	19.1	3	Parameters here are for planned ACT brassboard design with uncooled detector. Additional design variations such has higher spectral resolution or further miniaturization are possible, depending on choice of dispersive optics. The system uses computational imaging, overdetermined measurements, and a spectral coding mask to improve throughput and SWaP. By replacing or changing a spectral coding mask, we can reconfigure the instrument capability. For example, CRISP can trade off area coverage rate or spectral resolution versus sensitivity over a wide range, enabling new options for CONOPS in a small satellite
Reduced Envelope Multispectral Instrument (REMI)	Dennis Nicks (Ball)	SLIT-15-0027	dnicks@ball.com	VSWIR + TIR		50 x 50 x 50			3	
CIRiS- Compact Infrared Radiometer in Space	Osterman (Ball)	INVEST-15-0023	dosterma@ball.com	7.5 to 13 µm	.91 to 5.5	18 x 18 x 10	1.22	12.2 x 9.2	8	4U instrument; fits 6 U S/C. On narrow band at 12.2 microns; another at 10.6 microns, then broadband 7.5 to 13 microns. The instrument architecture is modular and the optics are easily swapped out. We have recently developed a new CIRiS optics design for a proposal that has 4 bands instead of 3; spectral resolution from 0.4 um to 6.2 um and FOV 11.5 deg x 15.6 deg.
Advanced Technology Land Imaging Spectroradiometer (ATLIS)	J. Puschell (Raytheon)	SLIT-15-0022	jjpuschell@raytheon.com	VSWIR	Similar to OLI	29 x 29 x 46	16.6	16 X 1	4	FOV?: 15.5 x 1.0 deg^2
MiniSpec	J. Ranson (GSFC)	IIP-16-0049	jon.ranson@nasa.gov	0.45 - 1.65 µm	10	65 x 92 x 116 cm	0.042	14.8	3	The full spectral response will be the 450 to 1650nm portion of the spectrum with 10nm spectral resolution.
Integrated Photonic Imaging Spectrometer	S. Sandor--Leahy (NGAS)	SLIT-15-0026	stephanie.sandor-leahy@	1.36 - 1.66 µm	3 or 6				3	FOV?: An SLI foreoptic requires a wide field-of-view (FOV) in cross track (15°) and an along-track FOV (~2°) to accommodate either all the required filter bands for an MSI instrument or multiple spectrometers for a traditional HSI approach. Since the HAWC layers are thin even with a TDI approach the along-track FOV remains small (~0.3°) easing the telescope design.
Tunable Light-guide Image Processing Snapshot Spectrometer (TuLIPSS)	T. Tkaczyk (Rice)	IIP-16-0046	ttkaczyk@rice.edu	0.4 - 1.7 µm	1 to 10 or 20				3	Working on a SWIR prototype
THERMAL INFRA-RED COMPACT IMAGING SPECTROMETER; HyTI Hyperspectral Thermal demonstrator	R. Wright (U. HI)	IIP-13-0008; InVEST 2018	wright@higp.hawaii.edu	8 - 14 µm		28 x 36 x 56	0.24	4.18° × 3.34° (horizontal × vertical)	6	Airborne demonstrator was the IPP; HyTI is a cubesat demonstration

*Courtesy Bob Smith, ESTO

SBG-relevant ESTO Instrument Investments*

- 8 VSWIR instruments can be binned into 0.4 to 1.7 μm, and 0.4 to 2.5 μm spectral range options
- 6 TIR instruments divide up into multi-band radiometers and bolometers
- Only 1U instrument is CHRISP (TRL-2)
- Three others - GEO TIR, SWIS and CIRIS - are 2-4U.
- Others appear to be Smallsat-sized - between 4U and up to 125 U (50 x 50 x 50 cm)

- 2 of the ESTO investments (HyTI and CIRIS) are InVEST cubesat demonstrations, with potential launch dates 2020 and 2022-3

Existing and Planned VSWIR Hyperspectral and Thermal IR Spaceborne Systems

Mission	Sponsor	GSD (m)	Spectral Range (μm)	Swath (km)	Spectral res (nm)	Pointing?	Mass (kg)	Dimensions	Launch Date	Comment
CHIME	ESA	20 to 30	0.4 to 2.5	> 200	10				TBD	Not yet approved to go forward; lots of TBDs
EnMAP	DLR	30	0.4 to 2.5	30	6.5 or 10	Yes	369	1.8 x 1.2 x .7 m	2020	Acquisitions limited to 5000 km by onboard memory
HyperScout	ESA	40	0.4 to 1.0	164	13	Yes	1.1	10 x 10 x 10 cm	2018	1U instrument on 6U cubesat platform (GOMX-4); h=300 km
CHRIS on Proba-1	ESA	17-36	0.4 to 1.0	13-18	1.3 to 11	yes	14	.2 x .3 x .8	2001	Still operating
HICO	NASA	90	0.4 to 1.0	50	5.7	yes	500	.8 x 1 x 1.85 m	2009	Decommissioned in 2014; ISS accommodation mass/vol penalty
PRISMA	ASI	30	0.4 to 2.5	30	12	Yes	90	.8 x .6 x .8 m	2019	
HySIS	ISRO	30	0.4 to 2.4	30	10	Probably	~160	.7 x 1.4 x 1.2	2018	Launched in Nov 2018; estimated Vol and P/L mass fraction 0.4
DESIS	DLR	30	0.4 to 1.0	30	2.6	Yes	88		2018	On ISS
Hyperion	NASA	30	0.4 to 2.6	7.5	10	Yes	49	.4 x .8 x .7 m	2000	Only one 10 x 10 km scene per orbit; decommissioned
TianGong-1 HSI	China	10 to 20	0.4 to 2.5	10	10 to 23	Probably			2011	Data not accessible to US investigators; not operational
AHSI on GaoFen-5	China	30	0.4 to 2.5	40	5 and 10	Probably	147	1 x 1 x 0.6 m	2018	Data not accessible to US investigators
HISUI	Japan	30	0.4 to 2.5	20	10 to 12.5	Yes	240	2.3 x 1.5 x 1.6 m	2019	ISS interface box vol penalty
SHALOM	ASI-ISA	10	0.4 to 2.5	10	10	Yes	120		2019	
HypXIM	CNES	8	0.4 to 2.5	15	10	Yes	60	.6 x .6 x .8 m	2023	
EMIT	NASA	30	0.4 to 2.5	36	10	Yes	194	.5 x .8 x1.0	2022	ISS interface box mass/vol penalty
GHG Monitoring	CA	15-30	0.4 to 2.5	18 to 48	5 or 10	Yes	50	.5 x .8 x1.0	2022	Concept Study. Could be first of a constellation of n = 20
M3	NASA	70	0.4 to 3.0	40	10	Yes	8.2	.5 x .5 x .5	2008	From lunar orbit at h=200 km
FLEX	ESA	300	0.3 to 0.7	160	0.1 to 2	No	130	1 x 1 x 0.8 m	2022	Fluorescence measurements
Watersat	CSA	100	0.4 to 1.0	240	6	Yes	76	.4 x .8 x 1.2 m	2024/5	High SNR ~ 1000 for ocean color apps
PACE	NASA	1000	0.4 to 0.9	1550	5	No	241	1 x 1.2 x 1.1 m	2022	
TIRS	NASA	100	10.8 and 12	185	2 bands	No	236	.8 x .8 x .4	2013	
MODIS	NASA	1000	7 to 14	2330	N/A	No	229	1 x 1.6 x 1 m	1999	
EcoStress	NASA	70	8 to 12	384	5 bands	?	490	1.9 x .8 x .9	2018	ISS interface box mass/vol penalty
TRISHNA TIR	CNES/ISRO	50	8.6 to 11.5	900	4 bands	No?	106	1.0 x 0.75 x 0.65	2024	In Phase A

- VSWIR instruments can be binned into 0.4 to 1.0 μm, 0.4 to 1.7 μm, and 0.4 to 2.5 μm spectral range options
- Only 1U instrument is HyperScout on GOMX-4 (ESA) - 0.4 to 1.0 μm
- DESIS (DLR), PRISMA and possibly SHALOM (ASI-ISA) may be Smallsat (< 300kg) sized
- ISS-mounted instrument masses/volumes could be lower on a free-flyer
- Remainder are probably medium-class spacecraft compatible (> 300 kg)

Instrument Performance Modeling Example

Based on Achievable Ground Swath

(400 – 2500 nm, δλ 10 nm)

	Reference	Achievable Swath < 50 km	Achievable Swath 50 -100 km	Achievable Swath 100 - 150 km	Achievable Swath 150 - 200 km
Altitude (km)	400	400	400	500	500
GSD (m)	60	30	30	45	30
Detector pixel pitch (μm)	30	30	18	30	18
Telescope Aperture Diam (mm)	111.1	222.2	133.3	185.2	166.7
Focal Length (mm)	200.0	400.0	240.0	333.3	300.0
Achievable swath (km)	76.8	38.4	90	115.2	180

Slide courtesy Shannon Zareh, JPL

- Pushbroom instruments
- Achievable swath is dependent on the focal plane array size
- 210 pixels required (on the spectral dimension of the FPA) for δλ of 10 nm
- Telescope optics size: aperture diam x focal length x focal length
- Dyson spectrometer optics size: (2x slit length) x (10x slit length) x (2x slit length)

Existing US Multi-Band VSWIR & Thermal IR Spaceborne Systems

Mission	Sponsor	GSD (m)	Spectral Range (µm)	Swath (km)	# Bands	Pointing?	Orbit	Crossing Node	Repeat period	Launch Date	Comment
Landsat 5 TM	NASA	30 120	0.45 to 2.35 10.4 to 12.5	185	5 1	No	705 km SSO	9:45 AM	16 days	1984	Decommissioned in 2013
Landsat 7 ETM+	NASA	30 120	0.45 to 2.35 10.4 to 12.5	185	5 1	No	705 km SSO	9:45 AM	16 days	1999	Still operating; plan to refuel in 2020
Landsat 8	NASA	15 30 100	0.5 to 0.68 0.45 to 2.35 10.6 to 12.5	185	1 7 2	No	705 km SSO	10:00 AM	16 days	2013	Still operating
MODIS on Terra	NASA	250 500 1000	0.62 to 0.88 0.46 to 2.2 0.4 to 14.4	2330	2 5 24	No	705 km SSO	10:30 AM	Daily	1999	Still operating
MODIS on Aqua	NASA	250 500 1000	0.62 to 0.88 0.46 to 2.2 0.4 to 14.4	2330	2 5 24	No	705 km SSO	13:30:00 AM	Daily	2002	Still operating
ASTER on Terra	JAXA	15 30 90	0.52 to 0.86 1.6 to 2.4 8.1 to 11.7	60	4 6 5	Yes	705 km SSO	10:30 AM	16 days	1999	Still operating
MISR on Terra	NASA	275	0.42 to 0.89	360	4	No	705 km SSO	10:30 AM	16 days	1999	Still operating; multiple fixed viewing angles - (9) along-track in each band
VIIRS on Suomi NPP	NASA	375 750	0.6 to 12.4 0.4 to 12.5	3040	5 17	No	705 km SSO	13:30:00 AM	Daily	2011	Still operating
AVHRR/3	NOAA	1090	0.6 to 12.5	2900	5	No	805 km SSO	13:50:00 AM	Daily	1998	Still operating
GOES-15	NOAA	1000 4000	0.52 to 0.71 3.7 to 13.7	Whole disk	1 4	Yes	GEO (Americas)	N/A	3 minutes	2010	Can scan 3000 x 3000 km area in 3 min
GOES-16 and GOES-17	NOAA	500 1000 2000	0.6 to 0.7 0.45 to 1.7 1.4 to 13.6	Whole disk	1 3 12	Yes	GEO 75 and 113 W	N/A	15 mins	2016 2018	2 platforms. Can scan 3000 x 3000 km a
ALI on EO-1	NASA	10 30	0.48 to 0.69 0.43 to 2.4	37	1 9	Yes	705 km SSO	10:15 AM	16 days	2000	Retired in 2017
SeaWIFS	NASA	1100	0.4 to 12.5	2801	10	No	705 km	12 noon	Daily	1997	Retired in 2010
DSCOVR	NASA	20000	0.32 to 0.78	Whole disk	10	No	L1	12 noon	Daily	2015	At Sun-Earth L1
OCO-2	NASA	2000	0.76 to 2.1	7	3	No	705 km SSO	13:30:00 AM	16 days	2014	Nadir viewing, very narrow swath; OCO-3 has pointing
OCO-3	NASA	2000	0.76 to 2.1	7	3	Yes	400 km ISS	N/A	~19 days	2019	OCO-3 has pointing

SBG Architecture Trades

Orbit Characteristics

- For VSWIR observations, assume orbit is SSO, near-polar, at 705km altitude (same as A-Train), with node crossing between 10:30 am and 1:30 pm
- Could do a trade to look for other SSO altitudes, e.g. ~500, 600 or 800 km
- For TIR observations, orbit can be the same as VSWIR, or a non-SSO orbit (multiple orbit options)

SBG Architecture Trades

Data Rates and Data Volumes

- Data rate is given by:

$$D_R = \left[\# \frac{Bits}{sample} \times SW \times \frac{Spectral\ range}{Spectral\ resolution} \times \frac{V_{SC}}{GSD} \times \frac{1}{GSD}\right]_{VSWIR} + \left[\# \frac{Bits}{sample} \times SW \times \#Bands \times \frac{V_{SC}}{GSD} \times \frac{1}{GSD}\right]_{TIR}$$

- For selected orbit altitude, coverage objectives are satisfied by:
  - SW = 185 km (VSWIR)[1]
  - SW = 400 km(TIR)
- Aggregated 'instantaneous' data rate for these swaths is ~4.1Gbps (95% VSWIR data, 5% TIR – 5 bands)
- Assuming 4:1 Data Compression this becomes ~1Gbps
- Assuming a 15% Duty Cycle (for daytime VSWIR obs. over all land surfaces), and 4:1 data compression, Data Vol. per day is ~ 15 Tbits[2]

1. Note that swath coverage can be achieved by a single instrument, or by multiple instruments on smaller platforms
2. Total data volume generated by <u>all</u> NASA missions in 2016 was 12.1 TB/day

SBG Architecture Trades
Data Rates and Data Volumes

- How can we downlink such large data volumes?
- For 1 or 2 spacecraft options:
  - 2-3 Gbps Ka-band RF downlinks on nearly every orbit
  - TIR data rates will likely be lower
  - Optical D/L capability at 200 Gbps in a single pass per day (TBIRD STMD tech demo)
- For constellation options (multiple S/C):
  - Each spacecraft collects a significant fraction of the desired coverage
  - Data volumes per spacecraft are lower
  - Example: 800 Mbps D/L (optical) on 6 or more cubesats

Pre-Decisional – For Discussion Purposes Only

SBG Architecture Trade Space

Mission Category	Flagship[2]	Large-Class	Medium-Class	Small-Class	Constellation[1]	Null
# Platforms	1	1	1 or 2	2	16 / 10+1 / 6+1	0
Launch Vehicle	Vulcan or Falcon-9		Electron or Virgin	PSLV	Vega	Secondary
# Separate Launches	1		2		Multiple	
Instrument Suite[2]	.4–1 µm or .4–1.7 µm or .4–2.5 µm			Hyper-spectral TIR or Multi-Band TIR or Bolometer		

International Contributions	Potential	Downlink Options	Ka-band, Optical, TDRS
Flight Spares	Potential	MOps Coord.	Commercial, GEO (NOAA)
Data Latency	High, Low	Mission Duration	3 yrs, 5-7 yrs
Pointing Off-nadir[3]	ON, OFF	OnBoard Processing	ON, OFF
Hosted Payload	Potential	Calibration	OnBoard, Vicarious

1. Constellation options are N cubesats/µsats or M cubesats/ µsats + 1 Smallsat/µsat

2. Add Polarimeter for Flagship combined with A in ACCP

3. For enhanced revisit frequency

SBG Architecture Trade Space

Notes:

A. Flagship option (Platform > 1000 kg) has SBG combined with the Aerosol mission, or other DO

B. Large and Medium-class options (300 kg < platform mass < 1000 kg) has both VSWIR and TIR instruments on one platform

C. Smallsat options are < 300 kg to fit smaller launch vehicles/ESPA ring

D. Null option implies NASA flies nothing; science data will come from Program of Record or non-NASA missions

E. Constellations may be a combination of cubesats (up to 12 U) and Smallsats; exact #s TBD

F. PSLV and Vega Launch Vehicles can only be used if contributed by ISRO or ASI

G. Secondary launch option is ESPA-ring or similar

H. Instrument options based on prior or current ESTO investments + literature search

I. International contributions are confined to L/V, Smallsat S/C, or cubesat observing element in a constellation – no larger spacecraft or primary instrument options

J. Flight Spares: some architectures may have room within the cost cap to produce instrument or cubesat element flight spares, which can be flown later to replenish system failures

K. Data Latency switch between High and Low assumes high Applications payoff for High Data Latency, and moderate payoff for Low Data Latency

L. Off-nadir pointing capability added for tasking to observe some phenomena at higher temporal frequencies, e.g. volcanic activity, or winter snow accumulation

M. Hosted payload option assumes that a suitable platform in an appropriate orbit can be identified

SBG Architecture Trade Space

Notes:

N. Downlink Options include Ka-Band to NEN ground stations, uplink to TDRS, and Optical comm.

O. Mission Operations Coordination means coordination with commercial data providers who may offer higher spatial resolution or temporal revisit, but in fewer spectral bands, or with NOAA's GOES-R etc. observation platforms, which have very high temporal revisit (15 mins) but coarse spatial resolution (kms).

P. Two nominal mission duration options are considered: 3 years and 5-7 years. Both have implications for satellite reliability and mission/instrument classification.

Q. OnBoard processing option reduces data on board the spacecraft to extract timely information, e.g. fire extent, oil spills, algal blooms, etc. which can be directly downlinked over a lower bandwidth capability, e.g GlobalStar or Iridium.

R. Calibration onboard means black body sources and lamps with known illumination. Vicarious calibration assumes the instrument performance is stable, and data products can be calibrated by comparison with other data sets.

Medium Sat Scenario Example

VSWIR (Pushbroom) | Multispectral TIR (Whisk-push)

Platform 1

VSWIR (Pushbroom) | Multispectral TIR (Whisk-push)

Platform 2

	VSWIR for Medium sat	Multi-spectral TIR for Medium Sat
Altitude (km)	600	600
GSD (m)	30 (A)	60
Detector pixel pitch (μm)	30 (A)	40
Telescope Aperture Diam (mm)	333.3	222.2
Focal Length (mm)	600	400
Achievable swath (km)	180	598.3
Spectral resolution (nm)	10	500
Sensitivity	SNR: 280	NEDT: 0.2K

Medium Sat	**Spatial**	**Temporal**	**Range**	**Sensitivity**
VSWIR per platform	A	A	A	A
TIR per platform	A/B	B/C	A	A
VSWIR combined	A	A	A	A
TIR platform combined	A/B	B	A	A

Smallsat Scenario Example

VSWIR (Pushbroom)

Platform 1

Multispectral TIR (Whisk-push)

Platform 2

Hyperspectral TIR (12U)

Multispectral TIR (Whisk-push)

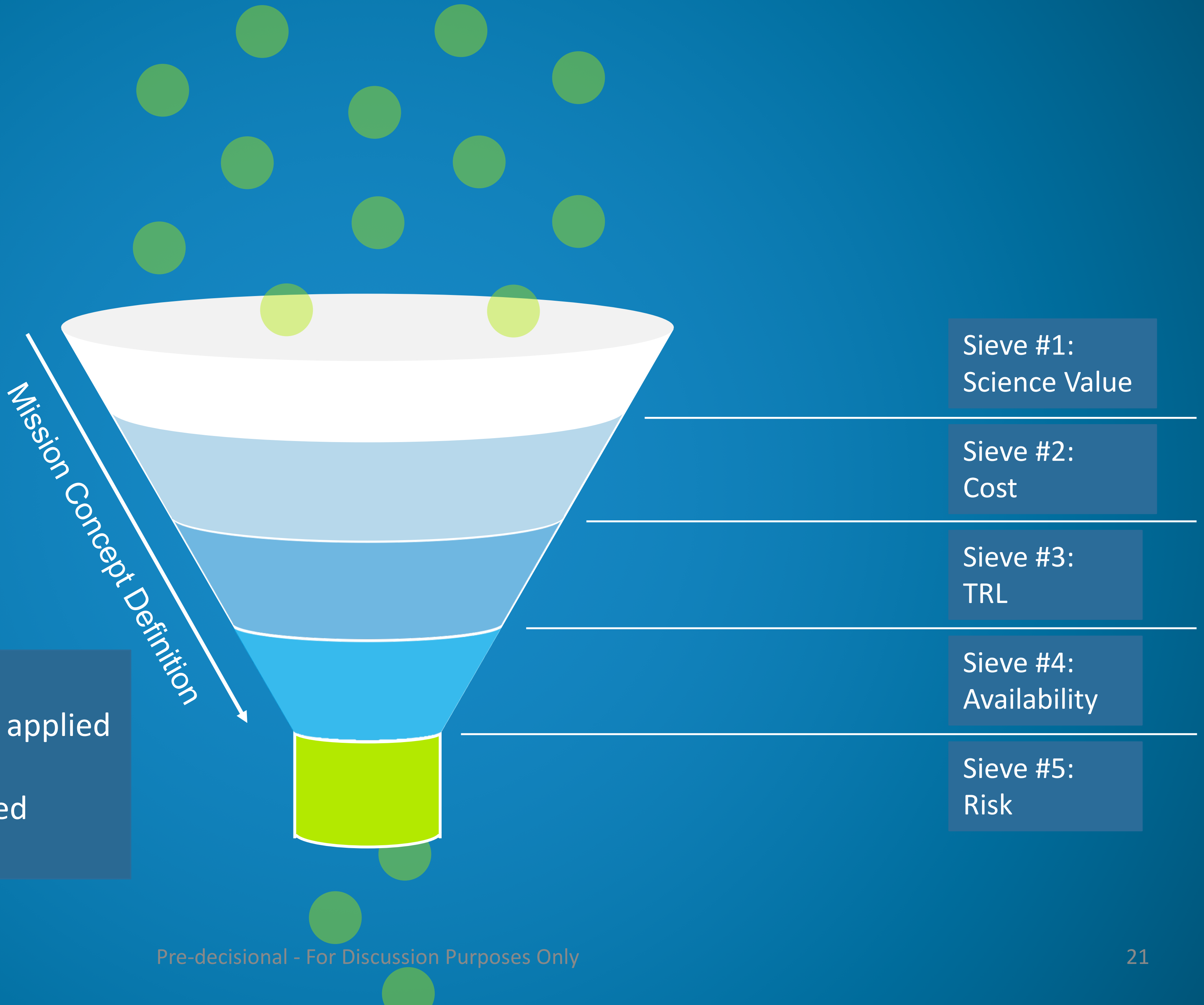
Multispectral TIR (Whisk-push)

Multispectral TIR (Whisk-push)

	VSWIR for smallsat	Multi-spectral TIR for SmallSat	Hyperspectral TIR for 12U
Altitude (km)	600	600	600
GSD (m)	60	100	80
Detector pixel pitch (μm)	30	40	40
Telescope Aperture Diam (mm)	166.7	133	166.7
Focal Length (mm)	300	240	300
Achievable swath (km)	240	436.8	102.4
Spectral resolution (nm)	10	500	40
sensitivity	SNR: 400	NEDT: 0.2K	NEDT: 0.1K

Small Sat	**Spatial**	**Temporal**	**Range**	**Sensitivity**
VSWIR	B	A/B	A	A
TIR (smallsat)	B/C	C	A	A
TIR (12U)	B	C	A	A
TIR combined	B	A	A	A

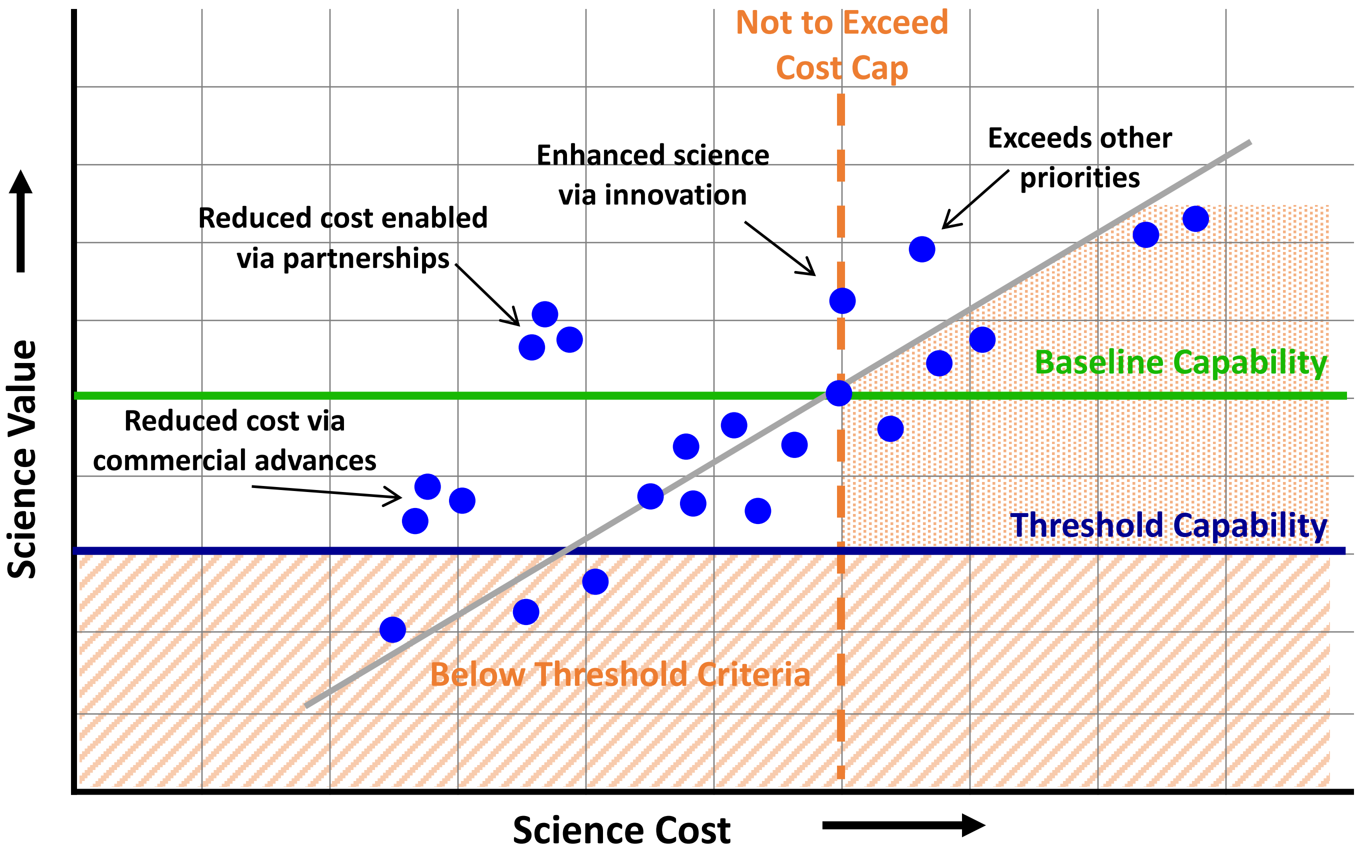
Applying Value Metrics



NOTIONAL SIEVING PROCESS:

- Other value metrics may be applied
- In different order
- Iterative process may be used

Value Framework Assessment



Notional graphic showing Science Value vs. Cost. Gray diagonal line depicts a conventional cost performance profile. Blue dots depict individual architectures. Reduced cost to NASA may be enabled through strategic partnerships and/or innovative opportunities. Enhanced science return may be enabled through new technologies and/ or innovation. Architectures below the Threshold mission or above the cost target will not be considered.

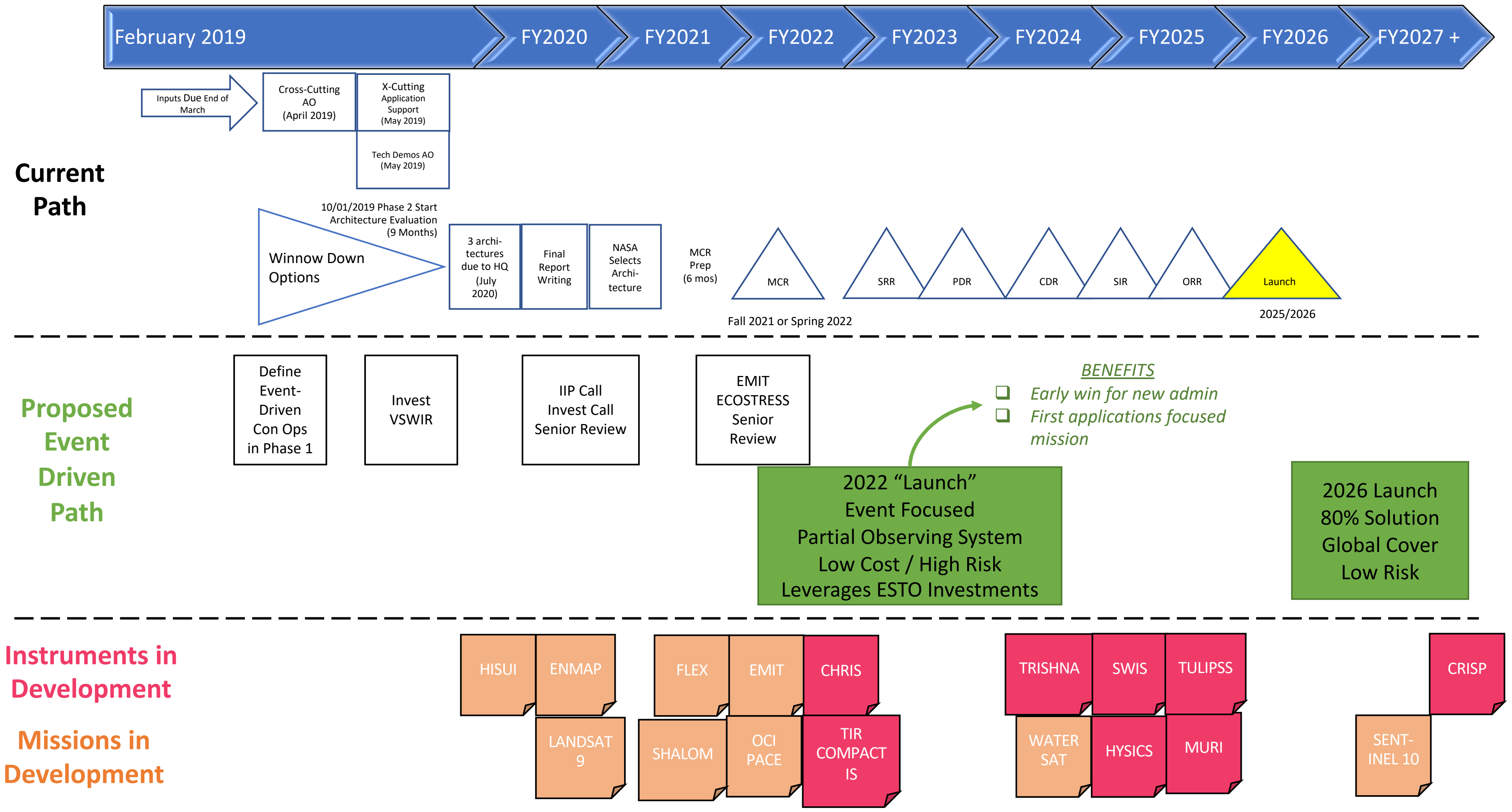
“Pathfinder” Option

Motivation: Rather do something in 2022 and not wait until 2026?

Suggested Approach: Focus on event focused operations concept launching in 2022, leveraging ESTO investments planned between now and 2022. *Does not eliminate the need for a second, more comprehensive concept that achieves “mow the lawn” coverage for 2026 launch*

- Use a combination of instruments that are already funded + another USD ~$10M earmarked for CubeSat investments with some extension of EMIT or ECOSTRESS
- ESTO concepts could be crucial to tackle the event-driven part of the study
- Could we get to a sizable chunk of the event-driven part of the study done this way?
- Test calibration approaches
- ESTO has its own funding. This is a **no-cost option** to SBG except for the development of the ops, concept, and operations cycles.
- Coordinate with other space agencies?
- Would need to continue to formulate the rest of the mission to make sure we have global coverage that meets the temporal revisit objectives

SBG Timeline



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